Journal of Hydrology, 19 (1973) 145–155

EFFECTS OF HEATED WATER DISCHARGE ON THE EVAPORATION FROM A RIVER SURFACE

JERZY JAWORSKI

Water Physics Division, National Institute for Hydrology and Meteorology, Warsaw (Poland)

(Accepted for publication November 13, 1972)

ABSTRACT

Jaworski, J., 1973. Effects of heated water discharge on the evaporation from a river surface. *J. Hydrol.*, 19: 145–155.

The investigations concerned the effects of thermal waters on the river evaporation process and the development of formulae, based on standard hydrological and meteorological data, for determination of evaporation from the Vistula river.

INTRODUCTION

Within the framework of the "Poland 3101" plan, which is undertaken in cooperation with the World Health Organization, investigations are being carried out in Poland into the effect of the discharge of heated water on changes in the heat balance components, evaporation and thermal conditions of an impounded river.

The main objectives of these investigations as discussed in this paper are: (1) to determine the effect of heated water discharge on the evaporation process from a river surface; (2) to develop a method to determine the evaporation from a thermally polluted river using meteorological and hydrological network data.

RESEARCH AREA, HYDROLOGICAL CHARACTERISTICS

The research as presented in this publication was carried out in the upper course of the Vistula river near Nowa Huta (Poland) in the years 1968–1969. The section of the Vistula river investigated is contained in the backwater beginning at the weir in Przewóz. The mean river depth amounts to 3.5 m, and the mean width is ca 100 m. The length of the river section affected by thermal water discharges is 2,200 m. Industrial thermal waters coming from the Lenin steelworks are carried away through the southern channel to the Vistula river (Fig. 1, channel *4*). The cooling-water intake from the steelworks is situated at a distance of 1,100 m below the discharge outlet (channel *7*). The NIHM Research Station (*8*) is about 2,200 m downstream from the thermal water outlet. The station included a land base, a water base and a pavilion equipped with the recording apparatus. The meteorological and hydrological measurements were carried out at these bases and partly at the

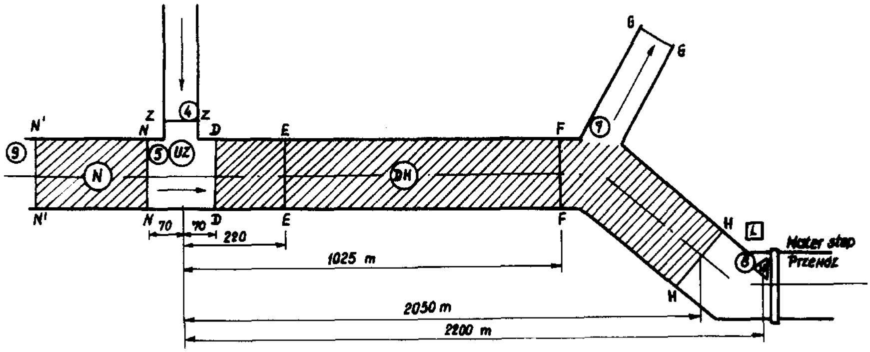

Fig. 1. Location of the meteorological posts, measurement profiles and points and the investigated stretches of the Vistula river near Nowa Huta. *N* = river stretch under natural conditions; *UZ* = area directly below the heated water outlet; *DH* = river stretch between profile *D* and *H*; *L* = land meteorological station; *W* = water meteorological post with the floating evaporimeter; *4* = point of water temperature measurement; *EE* = cross section *E*.

cross sections and measurement points indicated in Fig. 1.

The mean yearly flow of the Vistula river in the Przewóz gauge cross-section amounted to 85.0 m^3/sec for the years 1951–1960, the mean minimum flow in summer for the same period amounted to 28.7 m^3/sec. In the investigation period from November 1968 to October 1969 the flow of the Vistula river varied from 35.1 to 303 m^3/sec, with an average of 75.7 m^3/sec. The mean flow velocity on the investigated section varied from 0.08 to 0.80 m/sec. The flow of the discharge and the flow of the intake were almost constant and amounted to 9.0 and 10.6 m^3/sec, respectively. The variations of the "natural" water temperature ranged from 0.9°C to 25.6°C, the temperature of the thermal water discharge (cross-section *Z*) varied from 9.4°C to 34.6°C. The annual mean precipitation amounted to 645 mm, the annual mean air temperature to 7.7°C and the annual mean wind velocity to 2.3 m/sec.

RESEARCH METHOD

The results obtained from the thermal pollution investigations carried out on the Vistula river and on the Konin lakes have shown a significant relationship between the amount of evaporation and the cooling possibilities of rivers and lakes. Heat losses caused by evaporation processes predominate amongst the heat balance components, which represent the heat exchange between the water surface and the atmosphere (Jaworski, 1971b). The evaporation from a free water surface can be measured directly by means of floating evaporimeters installed on a raft. There are also other methods for determining the evaporation. One of the best seems to be the eddy-correlation method (Swinbank, 1951). Unfortunately we have not in Poland the precise and sensitive instrumentation needed in this method. There are also W.M.O. recommendations (W.M.O., 1966) for the use of the heat balance method which is often employed as a standard method; this makes it possible to determine the evaporation by the heat balance equation, namely:

$$E = \frac{Q_f + Q_v - Q}{\rho[L(1 + R_B) + ct_0]} \quad \text{(cm/day)} \tag{1}$$

where Q_f = the radiation balance of the water surface, Q_v = net heat advection, which is the net energy contained in water entering and leaving the water body investigated, Q = change of heat energy storage in the water body (all terms in cal./cm^2 day), ρ density of water (g/cm^3), L = latent heat of vaporization at temperature t_0 (cal./g), R_B = Bowen ratio, c = specific heat of water (cal./g °C), t_0 = temperature of water surface (°C).

The evaporation value may be calculated also using eq. 2, if the turbulent transfer coefficient "k_w", the air density "ρ_a" and the humidity gradient $\partial q/\partial z$ are known:

$$E = -\rho_a k_w \, \partial q/\partial z \tag{2}$$

Above-mentioned methods require many hydrological and meteorological measurements, which is often a difficult and complex problem. Therefore different empirical and half-empirical formulae have been developed, based on meteorological and hydrological network data.

For example so called "mass transfer" equations are often used. In general they agree that evaporation is proportional to the product of the wind and humidity gradient, and sometimes also the temperature gradient is taken into account. One of such equations is the Braslavski and Vikulina formula 2:

$$E_1 = 0.13\,(1 + 0.72\,u)\,(e_0 - e) \quad \text{(mm/day)} \tag{3}$$

A similar formula was developed in the U.S.S.R. (Gław. Upravl. Gidrom., 1966) for thermally polluted lakes, where a higher thermal stratification appears above the lake surface than under natural conditions (formula 4):

$$E_2 = 0.104\,(k_0 + u)\,(e_0 - e) \quad \text{(mm/day)} \tag{4}$$

Also the American formula (eq. 5), based probably on the results of the Lake Hefner and Lake Colorado studies (W.M.O., 1966) does not differ much from the above mentioned equations:

$$E_3 = 0.131\,u(e_0 - e) \quad \text{(mm/day)} \tag{5}$$

In these equations u = the mean wind velocity at the height of 2 m above the water surface (m/sec); k_0 = coefficient depending on the difference $t_0 - t$, $k_0 = f(t_0 - t)$ where t_0 is the water-surface temperature (°C), t = air temperature at the height of 2 m (°C); e_0 = saturation water vapour pressure corresponding to the water-surface temperature (mbar); e = vapour pressure in the air at the height of 2 m above the water surface (mbar).

Taking into account the research results obtained in evaporation investigations made simultaneously with the heat balance and evaporimeter method (floating evaporimeter) it seems that the latter gives no less satisfactory results than the heat balance method recommended by W.M.O. Investigations made by Richter (1966) on Lake Stechlin have shown that the amount of evaporation measured by a floating evaporimeter type GGI–3000 is close to the one determined with the heat balance method. Differences between evaporation values obtained by these two methods were less than 6%. Also investigations made in Poland by Jurak on the Konin lakes gave similar results, with differences not exceeding ca. 10% (Jaworski, 1971a).

In the Vistula river investigations the evaporation was measured by a floating evaporimeter type GGI–3000 installed on a raft. An attempt to use the heat balance method for evaporation calculations has brought negative results because of the insufficient accuracy of the heat advection term determination over such a short river stretch (Jaworski, 1971a).

The results of the evaporation measurements made at one point were recalculated for a larger river surface according to the following formula, recommended in (Gław. Upravl. Gidrom., 1966):

$$E = E_{GGI} \frac{e_0 - e}{e_0' - e} \quad \text{(mm/day)} \tag{6}$$

where E = evaporation of the investigated river surface (mm/day), E_{GGI} = evaporation measured by the floating evaporimeter type GGI–3000 (mm/day), e_0 = saturated water vapour pressure corresponding to the temperature of the river surface (mbar), e_0' = saturated water vapour pressure corresponding to the water surface temperature of the floating evaporimeter (mbar).

One of the additional problems which appears in each research method is the replacement of missing data. In the Vistula river investigations we also had some gaps in the evaporation measurements – mainly in periods of high wind speeds, at high flow and also in winter days, when the evaporimeter was sometimes frozen, although the river was free of ice.

An attempt to apply one of the empirical formulae (eq. 3–5) for the replacement of missing evaporation data was made, but without success. The results obtained showed, that evaporation values computed by the above formulae differed too much from the data received by the evaporation method (Fig. 2); the mean error (σ) being (for 10 days evaporation values):

For the Braslavski and Vikulina formula 3:	$\sigma = \pm 23\%$
For the Russian formula 4:	$\sigma = \pm 24\%$
For the American formula 5:	$\sigma = \pm 41\%$

Under such circumstances a further attempt was made to develop a "mass transfer" formula, which would be acceptable for the existing research conditions. The general form of the proposed formula is:

$$E_4 = a(u + 1)^n (e_0 - e) + b \text{ (mm/day)} \tag{7}$$

Having 46 daily evaporation values and as many values of average daily wind speed, saturation water vapour pressure and actual vapour pressure of the air for the period in which the evaporation values were measured, the "a" and "b" coefficients have been calculated

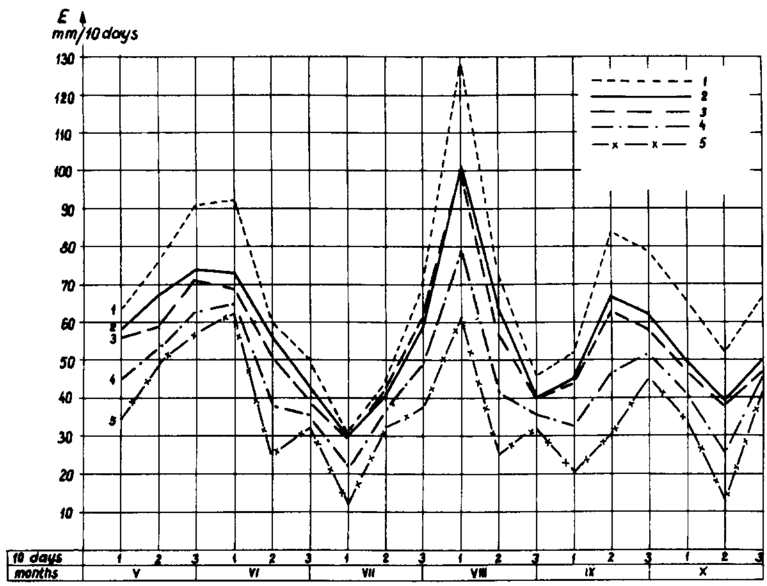

Fig. 2. Values of evaporation from water surface of the Vistula river loaded with thermal discharges (stretch *DH*), measured and those calculated by different empirical formulae (for ten days' periods from May to October 1969, amounts in mm). *1* = evaporation calculated according to Russian formula (eq. 4); *2* = evaporation measured by the evaporometric method (eq. 6); *3* = evaporation determined according to the formula developed for the Vistula river near Nowa Huta (eq. 8); *4* = evaporation calculated according to Braslavski and Vikulina formula (eq. 3); *5* = evaporation calculated according to the formula applied in the U.S.A. (eq. 5).

resulting in the following formula*:

$$E_4 = 0{,}225\,(u+1)^{0.5}\,(e_0 - e) - 0.02\ \text{(mm/day)} \tag{8}$$

The equation makes it possible to calculate the daily evaporation values for Vistula river conditions, where the water surface temperature varied from 2.9°C to 29.0°C; correlation coefficient $r = 0.97$, the mean error $\sigma = 0.4$ mm. The equation is significant for $P_u = 0.99$.

It must be mentioned here, that in earlier investigations of thermally polluted rivers, the evaporation calculations were made mostly by formulae developed for conditions which differ essentially from the thermally loaded conditions. For example Raphael (1962), who calculated the temperature of a heated river, computed the evaporation values according to the Lake Hefner equation. Delay and Seaders (1966) and Messinger (1963) employed a similar method. Velz and Gannon (1959) made a river-temperature prediction; applying the Meyer equation (1942) to river-evaporation computations. That formula was also used by Duttweiler et al. (1961) for the determination of hourly values of the Bowen ratio and heat conduction, although this equation was developed only for monthly

* It was assumed, that the coefficient "n" will be equal to 0.5 which agrees with the proposal of Bac (1968).

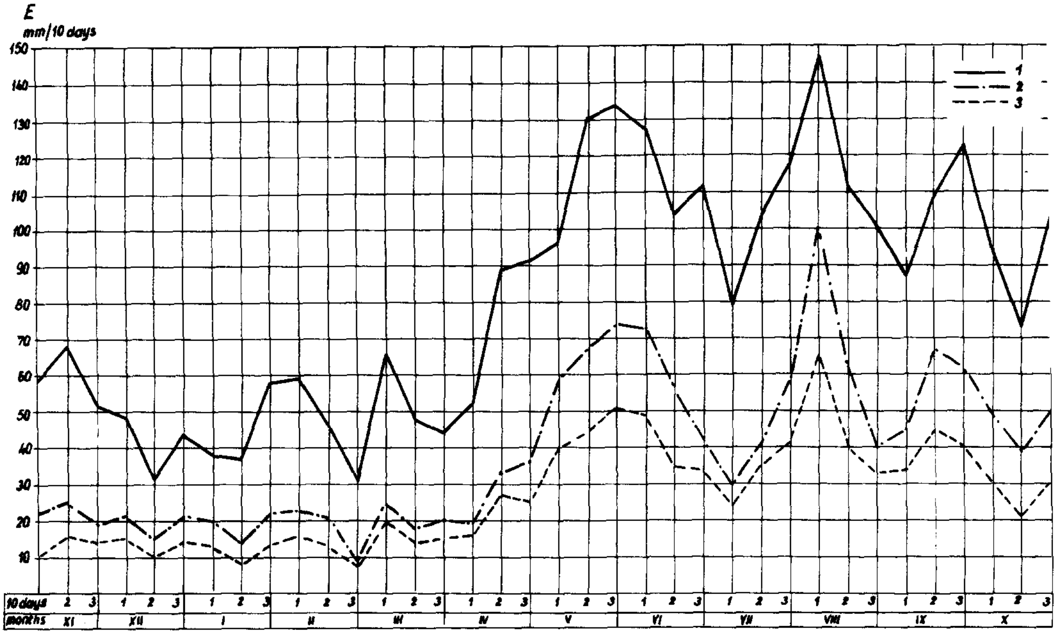

Fig. 3. The evaporation course from the water surface of the Vistula river under natural and thermally loaded conditions – period from November 1968 to October 1969; the measured 10 days evaporation amounts "E" in mm. 1 = evaporation under thermally loaded conditions, directly below the heated water outlet (UZ), 2 = evaporation under thermally loaded conditions (river stretch DH), 3 = evaporation under natural conditions (N).

amounts. It seems, that the application of such methods may result in considerable inaccuracies. One can see this for example from the results obtained under the Vistula river conditions (Fig. 2).

EFFECTS OF HEATED WATERS ON RIVER EVAPORATION

Results of evaporation measurements (E_{GGI}) and meteorological data obtained from the water meteorological station and those measured also above the different river sections made it possible to determine "E" values according to eq. 6, namely the evaporation values of the Vistula river stretches enclosed between the cross-sections D and E, E and F, F and H, D and H (DE, EF, FH, DH), the evaporation amounts directly below the outlet (UZ) and those under natural conditions*, which appear in the river upstream of the dis-

* Under the definition " natural conditions" we understand here the conditions of the Vistula river stretch upstream of the heated water discharge, which in fact does not entirely represent natural conditions. The river is in fact impounded and its temperature is somewhat higher than natural owing to the influence of heated water discharges from Skawinka and Kraków, which occur about 25 km upstream of the cross-section N.

charge outlet. A more detailed description of the applied measurement techniques is given in Jaworski (1971a, b).

The evaporation regime from the Vistula river under natural (*N*) and thermally loaded conditions (*DH* stretch and directly below the outlet, *UZ*) is shown in Fig. 3. The lowest evaporation was noted in the last ten days of February (6.6, 8.7 and 30.9 mm/10 days respectively for *N*, *DH*, and *UZ*). The highest evaporation occurred in the first ten days of August – respectively 66.4, 100.8 and 147.2 mm/10 days. The smallest difference between the evaporation under natural (*N*) and thermally loaded conditions (*UZ*) was observed in the second ten-day period of December (21.7 mm), yet the largest difference appeared in the warmer months – especially in the third ten-day period of September and in the first ten days of May and August (83.3, 83.1 and 80.8 mm/10 days – Fig. 3).

In general it can be concluded, that the influence of heated waters on the evaporation was greatest in the warmer months (V–IX). On the other hand in the colder period the effect was weaker.

Monthly and periodical river-evaporation figures are shown in Table I. It appears that the evaporation under natural conditions amounts in the summer time (V–X) to 692.9 mm, yet under thermally loaded conditions (*DH* stretch, *UZ*) to 1,019.0 and to 1,955.1 mm, that is 47% and 182% more.

The evaporation relations remained similar throughout the year. The yearly evaporation under natural (*N*), *DH* and *UZ* conditions reached 960.1 mm, 1402.0 mm and 2916.3 mm respectively, values that are about 442 mm and 1,956 mm or 46 and 204% higher than under natural conditions (Table I).

Of special interest is the low evaporation value in July compared with the high evaporation values in May and August, which is not typical under our climatological conditions (Jurak, 1970). The evaporation in July is even somewhat lower than in October (131.0 and 138.3 mm for the *DH*-stretch conditions). That is the more unexpected if we remember that this low evaporation value appears simultaneously with the highest radiation balance value Q_f (+226.6 cal./cm^2 day – Fig. 4). Comparing the river-water evaporation amounts in July and October one may get the impression that the evaporation pattern is in a high degree independent of the radiation balance (in October the average radiation-balance value of the water surface *DH* was negative and amounted to – 18.6 cal./cm^2 day – Fig. 4).

How is this phenomenon to be explained when we know that the evaporation process depends in great measure on the quantity of heat energy the active surface receives from sun and sky radiation? Researches carried out on the heat balance components of the river stretch have shown that the reason for such a situation may be on the one hand the additional heat coming from the thermal water discharges, or on the other hand from the heat energy stored in the river body, especially in the case of a large heat storage increase or decrease. Under such circumstances the time variation of evaporation may be more or less independent of the radiation balance.

Some results concerning the different heat balance components of the *DH* river-stretch are shown in Fig. 4, which indicates that in July the heat income from the net advection

TABLE I

Monthly and periodical evaporation amounts in mm under natural (*N*) and thermally loaded conditions (*DH* stretch, *UZ*) in the period from November 1968 to October 1969; Vistula river near Nowa Huta

River stretch	Months (1968)		Months (1969)										Period		Year	
	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI–IV	V–X	(mm)	(%)
N	40.8	38.9	34.6	36.0	48.6	68.3	133.3	117.6	101.1	139.6	119.2	82.2	267.2	692.9	960.1	100
DH	66.5	56.7	55.8	53.0	63.0	88.0	198.5	172.9	131.0	204.8	173.5	138.3	383.0	1,019.0	1,402.0	146
UZ	177.4	123.5	133.6	136.3	157.7	232.7	359.7	343.3	301.6	360.1	320.2	270.5	961.2	1,955.1	2,916.3	304

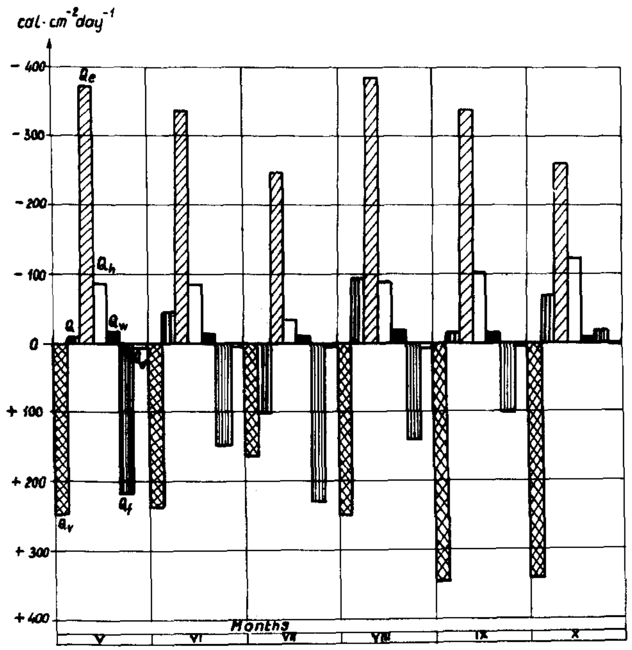

Fig. 4. The heat balance components of the impounded river stretch *DH* in the period from May to October 1969; mean monthly values in cal./cm^2 day, Vistula river near Nowa Huta. Q_v = net heat advection, that is the net energy contained in water entering and leaving the investigated river body, Q = change of heat energy storage in the river body, Q_e = heat energy utilised for evaporation, Q_h = heat energy conducted from the water body as sensible heat, Q_w= energy carried away by the evaporated water, Q_f = radiation balance of the water surface, Q_d = effective heat income caused by the rainfall.

term was much lower than in other summer months (in July the Q_v term was only 161.8, yet in May and September that component reached 246.7 and 340.4 cal./cm^2 day respectively). From Fig. 4 it is seen, moreover, that in July the term of heat energy storage change Q was positive and reached about 100 cal./cm^2 day on the average, which indicates that this amount of heat energy was utilised for the warming of the river body. Taking into account these considerations it appears that the low evaporation value in July can be explained.

An example of the influence of heated water discharges on the spatial variability of the free-water evaporation from the river is shown in Fig. 5, where daily evaporation values of selected days were presented under natural and thermally polluted conditions at different distances downstream of the outlet.

From an examination of the thermally polluted river stretch it is confirmed, that the discharges of heated water affected the differentiation of evaporation value principally in the region between the outlet (*UZ*) and the *DE* section. The evaporation varied at this stretch in a distinct curvilinear form. Farther from the outlet, the differentiation of evaporation became much smaller and formed nearly a straight line (Fig. 5). The greatest differentiation occurred in the region between *UZ* and *DE* (0–145 m) on 31. V. 1969 (6.0 mm),

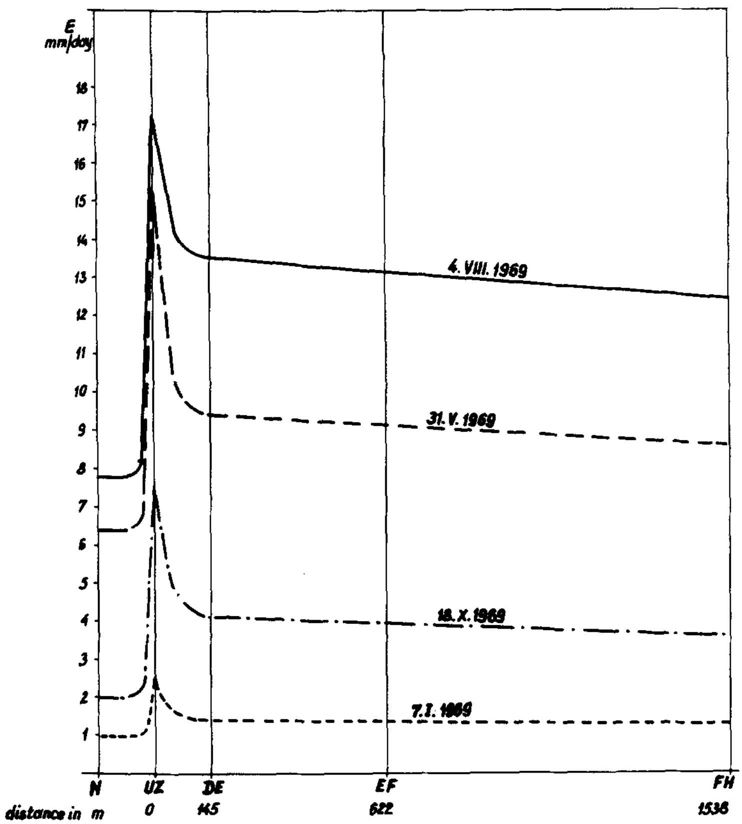

Fig. 5. An example of heated water effect on the spatial variability of river evaporation, Vistula river near Nowa Huta. Daily evaporation amounts of selected days in mm.

and the least on 1. I. 1969 (1.1 mm). The greatest evaporation variation in the region between *DE* and *FH* was noted on August 4, 1969 (1.1 mm), and the least on January 7, 1969 (0.1 mm). From Fig. 5 it can be seen, moreover, that the evaporation values were higher at each point of the thermally polluted river than under natural conditions.

SUMMARY

Research presented in this paper was carried out on an impounded stretch of the Vistula river near Nowa Huta (Poland) in the years 1968–1969. The main object of the investigations concerned the determination of thermal water effects on the evaporation process and the development of methods, to compute the Vistula river evaporation by formulae based on standard hydrological and meteorological data.

While determining the evaporation from a thermally polluted river surface by empirical formulae established for different conditions (for example for lakes) it is necessary to take into consideration the possibility of errors up to about 40% and in some individual cases

even to about 200%. Formula 8 developed for the Vistula river conditions makes it possible to determine the daily evaporation values with an accuracy of $\sigma = 0.4$ mm.

The effect of heated water on an impounded river has been a considerable increase of evaporation. The yearly evaporation values for the thermally loaded conditions (*DH*, *UZ*) amount to about 1,402 mm and 2,916 mm respectively. These values are about 442 and 1,956 mm or 46 and 204% higher than under natural conditions (about 960 mm yearly). The discharges of heated water led to variation in the evaporation values principally in the region between the outlet and the *DE* section. Farther from the outlet the variation was much smaller and ran nearly along a straight line. The value of evaporation was at every point of the thermally polluted river section higher than under natural conditions.

REFERENCES

Bac, S., 1968. Studies on evaporation from a free water surface, land evaporation and potential evapotranspiration. *Zesz. Nauk. WSR Wrocław*, XIII, 80: 7–68. (In Polish, with English summary.)

Braslavski, A.P. and Vikulina, Z.A., 1954. *Normy Isparenija s Poverchnosti Vodochranilišč*. Gidrometeorologičeskije Izdatelstvo, Leningrad, 211 pp.

Delay, W.H. and Seaders, J., 1966. Predicting temperatures in rivers and reservoirs. *J. San. Eng. Div.*, SA 1: 115–134.

Duttweiler, D.W., Jeffers, F.J., Kowal, A.L., Reyes, W.M., Lentz, J.J. and Sanders, W.M., 1961. *Heat Dissipation in Flowing Streams*. Rep. 1960–1961 Adv. Sem. Baltimore (Maryland).

Gławnyje Upravlenie Gidrometsłuzby, 1966. Materiały mezduvedomstvennovo sovescanija po probleme izučenija i obosnovanija isparenija s vodnoj poverchnosti. Valdaj, 64 pp.

Jaworski, J., 1971a. The application of an empirical model for the determination of water temperature in a thermally polluted impounded river (by an Example from the Vistula River near Nowa Huta). *Przegl. Geofiz.*, 1/2: 27–38 (in Polish).

Jaworski, J., 1971b. On a method of determination of the evaporation from a river surface loaded with thermal water discharges. *Wiad. Sł. Hydr. Met.* VII., 4: 27–36 (in Polish).

Jurak, D., 1970. Evaluation of evaporation from a water surface in Poland for the summer period 1956–1965 using direct measurements and climatological data. *Prace PIHM*, 99: 41–74 (in Polish).

Kaczmarek, Z., 1970. *Statistical Methods in Hydrology and Meteorology*. Warszawa, 312 pp. (In Polish).

Messinger, K., 1963. Dissipation of heat from thermally loaded stream. *U.S. Geol. Surv. Prof. Pap.*, 475–C, 104: C175–C178.

Meyer, A.F., 1942. Evaporation from lakes and reservoirs. *Bull. Min. Res. Comm.*, June.

Raphael, J.M., 1962. Prediction of temperatures in rivers and reservoirs. *Power Div. J.*, 7: 158–181.

Richter, D., 1966. Results of comparison measurements made with floating pans on Lake Stechlin. In: *Proc. Symp. Garda – I.A.S.H., Gentbrugge, Publ.*, 70: 258–265.

Swinbank, W.C., 1951. The measurements of the vertical transfer of heat. *J. Meteorol.*, 8 (3): 135–145.

Velz, C.P., Gannon J.J., 1959. Forecasting heat loss in ponds and streams. Presented on the 32nd Ann. Meeting, Fed. of Sewage and Industrial Wastes. Ass. Dallas (Texas).

World Meteorological Organization – IASH, 1965. *Symposium on Design of Hydrometeorological Networks*. W.M.O./IASH, Quebec, Que.

World Meteorological Organization, 1966. Measurement and estimation of evaporation and evapotranspiration. *W.M.O. Tech. Note*, 83, 121 pp.